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Open-source hardware as a model of technological innovation and academic entrepreneurship

Open-source hardware

The Brazilian landscape

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Received 6 June 2018
Revised 15 February 2019
6 September 2019
Accepted 29 October 2019

Abstract

Purpose – The purpose of this paper is to argue in favor of the open hardware philosophy (open-source hardware – OSH) as a technological innovation and academic entrepreneurship model in Brazil.

Design/methodology/approach – This argument is based on three pillars. The first one refers to a bibliographic review of theoretical frameworks related to academic entrepreneurship and technological innovation to emphasize the disruptive innovation capacity of academia. Second, a few elements related to the Brazilian political, economic and structural scenario, which entail a (more) favorable environment to technological innovation and academic entrepreneurship, is presented. Finally, concepts related to OSH and its business model are approached to demonstrate the facilitating effect toward the whole process.

Findings – As a result of the argument made herein, it is possible to perceive the viability of the OSH model in terms of entrepreneurship and technological innovation in the academic sphere, and to perceive its benefits before social and economic needs in areas such as health and education.

Research limitations/implications – There are no empirical or quantifiable data in the literature that enable comparison between OSH and traditional technological innovation models.

Originality/value – The considerations on the philosophical value of OSH and its business models are scarcely explored in international literature. As far as we know, relating OSH to technological innovation



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Innovation & Management
Review
Vol. 17 No. 2, 2020
pp. 177-195
Emerald Publishing Limited
2515-8961
DOI 10.1108/INMR-06-2018-0036

1. Introduction

Over a decade ago, the reports from the Global Entrepreneurship Monitor stated a propensity of the Brazilian people toward entrepreneurship by demonstrating a frequent elevated rate of entrepreneur activity, which places the country among the global leaders in the international ranking ([GEM – Global Entrepreneurship Monitor, 2002, 2015, 2017](#)). On the other hand, the fact that the national indexes of social and economic development are still far from being ideal ([UN/DESA – Department of Economic and Social Affairs of the United Nations Secretariat, 2015](#)), as well as the surprisingly low success or survival rate of new Brazilian companies (around 40 per cent during the first five years; [IBGE – Instituto Brasileiro de Geografia e Estatística, 2016](#)), shows a great gap between entrepreneurial urge and personal or macroeconomic success.

While the complex reasons for such mismatch are yet to be clarified, it is worth analyzing, proposing and discussing entrepreneurship strategies that, when disrupting standard models, can entail a different success potential. In this sense a non-conventional possibility is the technological innovation related to open-source hardware (OSH). It is a way to develop technology in a cooperative and open way, which advocates that every technical and intellectual content stemming from development (such as schematic diagrams, calculations, three-dimensional models and source codes) must be shared in a systemized manner through the available means of communication (especially the internet) to benefit any interested third party with no restriction regarding the use of information (commercial or not), geographical area or application.

The main purpose of this paper is to argue in favor of the OSH model as an alternative and viable business model for entrepreneurship and also as a sustainable development policy in the country, in which the Brazilian academic environment plays a leading role in the process. We intend to demonstrate that the adoption of the OSH philosophy can be a catalyst for one of the main missions of the academia: technological innovation and entrepreneurship.

2. Making the case for open-source hardware: method

The argument in favor of OSH is based on three distinct milestones, as shown in Illustration 1: bibliographic review of the theoretical framework regarding academic entrepreneurship, analysis of the country and establishment of OSH definitions.

The bibliographic review brings the main essential theoretical frameworks – historical or contemporary – on academic entrepreneurship, as well as the indicators that emphasize the important role played by the university in initiatives that break away from traditional models to delineate cause-effect relationships between academic activities and social and economic development through technological innovation, as well as disruptive entrepreneurship.

Initially, we searched the exact terms “open source hardware” in three important bibliographic databases in the field related to academic entrepreneurship: International Entrepreneurship and Management Journal; Research Policy; and Innovation & Management Review. It was possible for us to verify that the theme is virtually unexplored in the bibliography, considering there were no entry results for these research criteria. The same research accomplished in the Web of Science database resulted in hundreds of papers,

which, on the other hand, were about technological solutions that adopt the OSH model, which is not the scope of our research.

By using the databases of the above-mentioned journals, we searched for the terms “academic entrepreneurship,” “academic innovation” and “entrepreneur university” – restricted to review papers – in the entire historical series to locate systematic and comprehensive reviews on the theme, which could serve as a starting point for us. Among the results, we choose the study of [Schmitz, Urbano, Dandolini, de Souza, and Guerrero \(2017\)](#) because it was the most complete and recent one. Finally, we rerun our search, but this time without the review paper filter and only from 2018 onwards. This way, added to the references of [Schmitz *et al.* \(2017\)](#), we obtained the database that supported this step of the bibliographic review.

Among the articles obtained in this search, several ones handled regional landscapes by using qualitative approaches, as well as more objective methods, such as correlations between individual indicators and entrepreneurship levels ([Haeussler & Colyvas, 2011](#)), longitudinal studies on spinoffs and startups ([Civera, Donina, Meoli, & Vismara, 2019](#)), and correlation between systemized government data on higher education institutions and entrepreneurship indicators ([Budyldina, 2018](#)). The approach adopted in these studies guided the qualitative analysis accomplished herein. Apart from the constant political and economic turbulences, the conditions to start a business in the country and the recent advances in the business area over the past years are mentioned to enable a better understanding of the Brazilian scenario (Section 4). We describe some private sector initiatives, as well as government policies, that aim at encouraging the transformation of academic innovation into entrepreneurial initiatives ([Figure 1](#)).

Finally, the definitions of the OSH model were based on the books of Joshua Pearce and Alicia Gibb, as well as on other papers related to these books and authors, considering the novelty of the theme and consequently the scarcity of specialized bibliography. The definition, the background, the similarities and the differences between open-source software and the OSH business model are then discussed to demonstrate the strategic relevance and the sustainability potential inherent to this model (Section 5).

We conclude the paper with perspectives on the investigation of the theme, discussing the relationship between the OSH entrepreneurship model and innovation and the profile of the Brazilian entrepreneur. We also mention some historical social and economic needs of the country, which can indicate opportunities in terms of development potential (Section 6).

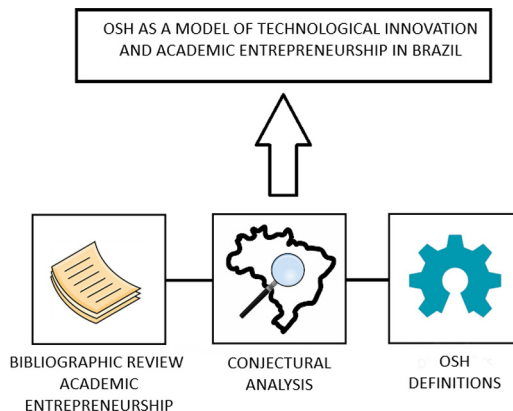


Figure 1.
Steps to create an argument in favor of OSH as a model of technological innovation and academic entrepreneurship in Brazil

3. Academic entrepreneurship, innovation and new business models

It is a widely accepted, and intuitive, fact that the level of entrepreneurial activity of a country is related to its economic strength (Kirchhoff, 1994, as cited in Souza Neto, 2008). However, this is not a directly proportionate relationship and there are several factors related to the type of business (e.g. necessity or opportunity entrepreneurship) that contribute to this equation (GEM – Global Entrepreneurship Monitor, 2002, 2015; De Barros & Miranda De Araújo Pereira, 2008; Ricca, 2004; Vasconcellos, Corrêa, & Reis, 2014). Still, there are evidences that opportunity entrepreneurship, closely related to technological innovation, is the most common entrepreneurship type in rich countries (Stel, Carree, & Thurik, 2005); such evidences indicate a path to be followed to promote the improvement of social and economic indicators. In the entire world, the university is an important player for technological innovation and opportunity entrepreneurship. This phenomenon is not exactly new and has been a subject of investigation in specialized literature. Schmitz *et al.* (2017) conducted a systemized bibliographic review to add to the establishment of theoretical frameworks in the area, such as the common definition of academic entrepreneurship and other relevant terms, the mapping of theoretical models and empirical methods, as well as the suggestion of guidelines for future research. The authors conclude that, despite fragmented and with poor theorization, there are some consensual and fairly established elements. Indeed, academic entrepreneurship can be defined as – with a certain variation among authors – the set of activities of a university that aim at aggregating economic and market value to the knowledge created in academic research to promote the regional social and economic development (Schmitz *et al.*, 2017).

This new role played by the university emerges naturally from the evolution (or revolution) of its purpose, which changed throughout history from knowledge dissemination to knowledge generation (research) to, finally, an economic application (entrepreneurship) (Etzkowitz, 1998). This second revolution of university started being better understood by the proposition of the triple helix theoretical concept, which catalogues and systemizes the promoting roles and interrelations between university, government and industry, all pressured by a new setting of economy based on knowledge (Etzkowitz, Webster, Gebhardt, & Terra, 2000) and supported by similarities between the organization of academic groups and companies (Etzkowitz, 2003b), as well as by the government role as a promoter of development (Etzkowitz, 2003a).

From then on, the new and third mission of university became clearer, which is related to the transmission of knowledge with commercial value to the society by means of technology transfer to the productive sector or supporting innovative startups, or even by means of entrepreneurial training, among other initiatives (Guenther & Wagner, 2008; Nelles & Vorley, 2011). Naturally, the transformation of the university became indispensable; the university starts to abandon its position on the “top of the Ivory Tower” toward an entrepreneurial one (Mainardes, Alves, & Raposo, 2011; Audretsch, 2014), which is more aligned with the need for regional development (Budyldina, 2018). On the other hand, this change in the profile of the university did not occur without any tensions; some conflicts arose because of the dichotomy between the university’s original purpose, i.e. training and research, and a possible entrepreneur vocation (Goldstein, 2010; Etzkowitz, 2013).

One of the most relevant aspects – considering both the academic and the managerial points of view related to the new entrepreneurial university – is the acknowledgment of the risks and success factors that shape academic entrepreneurship. Such issue has been approached through the analysis and systematization of different regional entrepreneurship ecosystems (Cavallo, Ghezzi, & Balocco, 2018) that looked for correlations between internal and external factors (Wood, 2011), such as academic productivity (Haeussler & Colyvas,

2011), performance of technology transfer offices (Belitski, Aginskaja, & Marozau, 2019), relationship between the researcher and the productive sector (Ferretti, Ferri, Fiorentino, Parmentola, & Sapio, 2018), venture capital (Rodríguez-Gulías, Rodeiro-Pazos, Fernández-López, Corsi, & Prencipe, 2018) and even international mobility of researchers (Civera Donina, Meoli, & Vismara, 2019). This line of investigation has benefited from the systematization of empirical models and objective methodologies capable of quantifying the relationship between the factors and the entrepreneurial ability and orientation, as well as the other purposes of training and research (Guerrero & Urbano, 2012; Tijssen, 2006).

The prominence of the academic sphere in entrepreneurship and technological innovation can also be seen when creating innovative productive arrangements and new managerial activities, as well as new business models (Schiavi & Behr, 2018). Such progress indicates a disruptive process, whose study and analysis can help understanding and accepting the OSH model, as it has happened in other technologies and arrangements (Sainio, 2004; Pereira, Imbrizi, Freitas, & Alvarenga, 2015). Specially, in these cases, the effective partnerships between public universities and the private sector have shown considerable benefits (Kampker, Gerdes, & Schuh, 2017). In this sense, we describe in the subsequent section some elements related to the Brazilian political and economic scenario that can eventually contribute to the creation of a favorable environment for the synergy of efforts between public and private spheres.

4. Conditions for academic entrepreneurship and innovation in Brazil

Despite the constant social and economic turbulences, one believes that Brazil has currently one of the most favorable scenarios for technological innovation enterprises of recent times, especially within public universities (Schmidt, Balestrin, Engelman, & Bohnenberger, 2016; Carvalho, Viana, & Mantovani, 2016; GEM – Global Entrepreneurship Monitor, 2015; Varichio, 2016). It is worth emphasizing that the prominence of technological and innovation development and, as consequence, qualified entrepreneurship, has been accomplished within the public sector, which is composed of universities and research centers because most part of the national scientific production is accomplished in federal and state institutions. This leadership role is evidenced by recent historical perspectives (Albuquerque, 1996), by the demand for policies that encourage innovation within companies (Matias-Pereira, 2013), as well as by official statistical data that show the predominance of public universities in patent deposits (INPI – Instituto Nacional da Propriedade Intelectual, 2017).

One of the factors that contribute to a more favorable environment to entrepreneurship, despite not being exactly new, is the notable volume of information on this theme that currently permeates the academic environment (Guenther & Wagner, 2008; Pardini & Santos, 2008). There are presently several university subjects related to entrepreneurship and technological innovation, especially in technology-based undergraduate courses. When such subjects are not compulsory, they are optional, and students are free to choose to attend classes or not. Despite the university subjects, there are several events related to the theme, such as lectures, seminars, workshops and whole meetings. For example, during the accomplishment of *Sociedade Brasileira para o Progresso da Ciência*[1] (SBPC) in 2017, there were three conferences and two round-table discussions that raised themes directly related to entrepreneurship and innovation. There are also graduate courses focused on entrepreneurship, whether in the form of regular or long-distance learning (distance education). In other words, it is possible to affirm there is an abundance of information on the theme, which can reach broad interested audiences.

Another important element in this equation is the ubiquitous administrative reorganization of universities, whose purpose is to promote entrepreneurship and technological innovation within its scope, as well as managing results and transforming them into wealth assets to the society and the institution itself (Plonski, 2005). Currently, almost every public university relies on offices responsible for managing the intellectual property, technological innovation and entrepreneurship centers, business incubators and junior companies, and many of the universities have already established their own science parks. This organizational infrastructure is the platform on which several systematized and important public initiatives operate in their several spheres and levels (Plonski, 2010). For example, the *Secretaria de Estado de Ciência, Tecnologia e Ensino Superior*[1] (SECTES, currently known as SEDECTES) of the Brazilian state of Minas Gerais, in collaboration with the *Serviço Brasileiro de Apoio às Micro e Pequenas Empresas*[2] (SEBRAE-MG), kept for several years the *Programa de Incentivo à Inovação*[3] (PII) initiative with the main goal of surveying the intellectual capital of the university in order to transform it into assets for industry and trade. After the accomplishment of the mapping, the institution and the researchers involved started promoting ways to effectively transform the potential found into patents, products, services, companies, etc. Another example is the program accomplished by the *Fundação de Amparo à Pesquisa do Estado de São Paulo*[5] (FAPESP) known as innovative research in small companies, whose purpose is to promote research and innovation within micro, small and medium-sized companies located in the state of São Paulo.

Regarding the government initiatives that facilitate the scientific research and the technological development while strengthening the relationship between university and industry, one can find a game changer in the new legal framework of science, technology and innovation (*Marco Legal de Ciência, Tecnologia e Inovação*, in Portuguese) in the beginning of the year 2016 (Alisson & Iziq, 2016). Such framework refers to legal adjustments that aim at improving the government and private support to scientific research activities and technological development, enabling the imports of equipment and consumables for research and enabling a broader cooperation between faculty enrolled in researcher and industry. Such law indicates that, for example, a professor can dedicate to industrial activities up to 416 h per year (previously, 120 h); it is now also permitted to earn a salary from such activities, which was previously prohibited.

Such initiatives indicate the emergence of a new culture within the Brazilian university. The university used to be afraid of the private sector because of a fear to lose its autonomy; currently, the university understands the importance of partnerships with the industry to solve historical social and economic issues (Audy, 2011). Such shift contributes to a more favorable environment to innovative entrepreneurship in the Brazilian university (Rocha Ipiranga, Ferreira De Freitas, & Alves Paiva, 2010), such as the one described by Kampker *et al.* (2017).

After establishing the background related to the initiatives of academic entrepreneurship and technological innovation in our country (at least part of them), it is now important to discuss some opportunities and strategies. As previously mentioned, the purpose of this paper is to emphasize a new type of technological innovation still little known in the Brazilian context, but very favorable to the academic environment: the open-source initiative, in particular, the OSH initiative.

5. Open-source hardware

5.1 Definition and background

According to the definition of the Open Source Hardware Association (OSHW), an OSH is a technological product, whose project is made entirely available to the public without additional costs to the information access so that anyone can study, modify, distribute and make it, considering that adaptations or the hardware *per se* can be freely used by third

parties or even sold by anyone[6]. Therefore, OSHWA establishes principles and standards of conduct to share information, which include the necessary documentation, the types of licensing, and others. Also, organization's principles determine the total free access to information and use, forbidding any restriction to types of applications or discrimination of users by, for instance, nationality, ethnicity, political orientation, and etc[7]. The purpose is to promote unlimited technological education, social development and human well-being in an environmentally sustainable way (Salem & Khatib, 2004).

Certainly inspired by its most famous counterpart, the open-source software, the OSH initiative emerged from sharing the product that lies at the border between software and hardware: the firmware. It is a software codified in programming languages that, in fact, describes electronic circuits (hardware description language – HDL). Software that uses HDL, when used for a specific type of hardware (like field-programmable gate arrays – FPGA), entails the creation of an electronic circuit through programmable connections among elementary components organized in matrices of the integrated circuit (Pearce, 2015).

From the starting point of firmware, sharing technology grew rapidly to contemplate other formats that included the layout of electronic circuits, the projects of printed circuit boards, control software and also mechanical designs of mechanisms or enclosures. The latter type of sharing information gained strength with the emergence of 3D printers that could create, through a process of plastic deposition in layers, a great variety of mechanical parts. For that, all it takes is to have computer files that contain the tridimensional design of the desired part that can be easily shared digitally. Particularly interesting, there has been for some time now 3D printers, such as RepRap, whose most parts can be printed by the printer itself, giving rise to a self-copying machine[8]. Still, the 3D printing technology evolved rapidly and gave rise to several distinct processes that enable the production of components with different quality, finishing and resistance levels in different speeds or with physical or mechanical restrictions, based on diverse inputs.

The development and sharing model of hardware solutions also increased considerably. There are currently movements in the global scenario related to open hardware, such as Fablabs, Hackerspaces, and Makerspaces, which operate throughout the world, including Brazil, with special emphasis on sustainability solutions (Ely, Smith, Fressoli, Abrol, & Arond, 2016). A quick search on the internet results in several sorts of open technological device, including amateur radio (Homebrew D-STAR Radio), robot (SAMSA II), camera (Elphel), gaming console (Uzebox), cell phone (ARA Project), audio equipment (Aurora 224) and even portable computer (Librem 15 Notebook). One can naturally find other products related to equipment and hardware solutions for scientific research, including optical devices, pH meters, spectrometers, centrifuges (Gibb, 2014; Pearce, 2014), infusion pumps (Wijnen, Hunt, Anzalone, & Pearce, 2014), miniature fluorescence microscope (Ghosh *et al.*, 2011) and biopotential systems (Open Ephys) (Siegle *et al.*, 2017). In fact, the European Organization for Nuclear Research (CERN) has a repository of OSH technologies derived in most part from the research that it conducts with its collaborators throughout the world. Opening technologies for sharing was the solution found by the CERN team to overcome technical difficulties imposed by projects, which is strongly related to the central argument of this paper, as shown in the next sections.

5.2 Academic advantages of the open-source hardware model

The great benefit of the OSH strategy relies essentially on the fact that it is a collaborative development model. The cycle of the product is not concluded after its dissemination throughout the world. On the contrary, this is where it starts because now the intellectual product is exposed to the scrutiny of thousands of specialized individuals who will look for

possible flaws and suggest solutions and improvements. Such as the central mechanism of science itself, the open model development has its own auto-correction processes and, this way, the technology developed under this paradigm tends to become excellent. It was with this exact perspective that CERN launched its OSH platform and repository ([CERN Media and Press Relations, 2011](#)).

In the book titled “Open-Source Lab,” [Pearce \(2014\)](#) systemizes the benefits of the OSH paradigm, as well as the opening of experimental protocols in a research laboratory, and therefore, in the academic environment. The author mentions five central benefits:

- (1) Massive peer-review in the development of material and projects, which leads to:
- (2) improvement of the experimental protocol and hardware project (often with costs radically reduced), which provides equipment with better performance;
- (3) increased visibility and therefore citations, which leads to:
- (4) increased funding opportunity and improved (student) recruitment; and
- (5) improved student training and education in the field of science.

These benefits favor the open model for scientific and technological development in the academic environment ([Gibb, 2014](#)). As a corollary to this, the scientific publishing company Elsevier launched a new indexed journal known as Hardware X, which is entirely dedicated to publishing OSH technologies for scientific research.

The adoption of the OSH philosophy benefits directly the production of high-level technological innovation in the academic environment and also in the private sphere, while providing economy of public research resources. In a paper published in 2015, Pearce carries out an OSH case study from the financial perspective taking into consideration the public investment made in the development of the project, which could easily be extended to any other initiative of the same kind ([Pearce, 2015](#)). This specific case addresses an infusion pump (an electromechanical system designed to infuse small amounts of liquids slowly through the plunger of a syringe) developed by [Wijnen et al. \(2014\)](#). Naturally, there was a remarkable difference between the costs of building an open version and acquiring the commercial version of specialized resellers. Now, when this difference is multiplied by the number of downloads of diagram files for the pump and the realization rate (number of file downloads that becomes a product), and this result is compared to the investment appraisal of American funding agencies (NIH and NFS) for the development of the open-technology project (total approximately US\$30,000), a return of investment between 460 and 8,300 per cent (US\$168,000-US\$2.5mn) is verified, which already gives the reader a notion of the savings for public coffers.

5.3 Open-source hardware business models: limitations of the intellectual property model and software inspiration

Considering that technological development and intellectual capital of a private company can benefit from an open model, it is worth questioning if the strategy can represent a valid business model and if an OSH company can be profitable. As mentioned before, the entrepreneur university has as one of its goals the aggregation of economic value to the knowledge it creates, promoting social and economic development. It is the job of the business model to define strategies through which the innovative enterprise will deliver value to the consumer in return for payments that will be converted into profit ([Teece, 2010](#)). Innovative technologies are usually related to disruptive business models ([Schiavi & Behr, 2018](#)) that, because of their counter-intuitive nature, face a considerable cognitive inertia in the corporate environment and in the adoption ([Tripsas & Gavetti, 2000](#)). In view of this,

before introducing an OSH business model, it is important to look for creative destruction in the studies of Schumpeter to demonstrate the limitations of the closed model, which protects – while also hiding – the creation through patents or copyright.

The opposite model to OSH, i.e. the closed intellectual property model protected by patents and copyright, is understood by some specialists in intellectual property as an obstacle to the progress of a company and its country. [Osborn, Pearce, and Haselhuhn \(2016\)](#) state that more than promoting innovation, patents induce leniency by defending an idea for a too long time. Joshua Pearce, in turn, reaffirms emphatically the words of Nobel Prize laureate Eric Maskin that “the standard intellectual property regime that was ostensibly established to foster innovation actually retards it” ([Pearce, 2014](#), p. 15).

Empirical studies show some results that start questioning the role of intellectual property as a booster of technological and economic development, both inside and outside the academic sphere. For example, a multilevel analysis of the effects of intellectual property aspects in the commercial behavior of professors concluded that the possession of intellectual property does not influence the academic entrepreneurial attitude ([Halilem, Amara, Olmos-Peñuela, & Mohiuddin, 2017](#)). There is also another study that analyzed data from dozens of countries over decades, concluding that the existence of strict patent systems has no relationship with the increase of productivity, which, in fact, is better related to the economic complexity of the country ([Sweet & Eterovic, 2019](#)).

The reasons for such surprising mismatch can be found in the original study of Henry W. Chesbrough. In his book, “Open Innovation: The New Imperative for Creating and Profiting from Technology,” Chesbrough brings a historical background of the intellectual property system, which was developed mainly in the USA during the post-war period ([Chesbrough, 2003](#)). At that time, patents were an important way to protect the stock of proprietary ideas deriving from the research sector of a large company before they could be absorbed and transformed into a product by the development sector. However, the corporate organization, labor relations and technologies changed drastically, which harmed the functionality of the patent system. Chesbrough mentions four reasons for such erosion:

- (1) the increase of the availability and mobility of skilled workers undermines knowledge retention;
- (2) the increase of the availability of venture capital facilitates the creation of spin-offs and other highly competitive enterprises;
- (3) the increasing tension deriving from Reasons 1 and 2 on stored ideas that end up being transferred elsewhere by other means; and
- (4) the increasing capability of external suppliers that bear knowhow of the production stages of a determined technology ([Chesbrough, 2003](#)).

The purpose of our study is not to announce the end of the intellectual property right system. There is no reason for such statement, especially considering that patents and copyright continue to be important in distinct scenarios of entrepreneurship, even in the open innovation system in an exceptional manner ([Weinberg, 2015](#)). We intend to clarify the limitations of the closed innovation system while comparing it to the open model, specifically the hardware one, to enable a comparison that supports the main arguments of this paper.

After the reflection made herein, the starting point to understand the open hardware business model is to acknowledge the successful cases of open-source software companies (Free Open Source Software – FOSS), which, as previously mentioned, is the forerunner of OSH. Let us take as an example the multibillionaire company Red Hat (Raleigh, USA), which

made its fortune – around US\$16bn and with annual revenues over US\$2bn – out of the commercial exploitation of the free and open-source operational system Linux (Darrow, 2016). In a similar vein to Red Hat, dozens of other companies dedicated to FOSS developed and transformed the software industry and the way through which it does business (Thakker, Schireson, & Nguyen-Huu, 2017). It is worth mentioning that large proprietary technology companies, such as IBM, Sun, Google and even Microsoft, have been exploring open sources in such a large scale that they can be considered the largest open-source companies on the earth (Asay, 2016).

It is clear that OSH and FOSS are different things and that the conclusions that are pertinent to the software cannot and should not be automatically applied to the hardware. Unlike the software, the hardware demands a physical accomplishment, i.e. a tangible, concrete and palpable product. It implies a series of logistics difficulties, such as the distribution of inputs and final products, and factory infrastructure for production, stocking and maintenance workshops, which involve higher costs. Once developed, the software can be replicated with no costs, which does not occur in the case of hardware. OSH presents some specific challenges that seem to be considerably bigger than the ones presented by FOSS (Gupta, Nowatzki, Gangadhar, & Sankaralingam, 2016).

Still, considering the example of FOSS and the first initiatives of pioneer companies and laboratories, it is possible to indicate a few guidelines of the OSH business model. Clarifying the dichotomy free versus open source (free as in free speech but not as in free beer) also helps to identify how OSH can be profitable. In other terms, open source does not mean free source. That is, the need for physical accomplishment of OSH – unlike FOSS – is one of the main niches to explore regarding the business model.

Along this line, distinct authors bring along some alternatives to add to the OSH business model (Gibb, 2014; Ferreira, 2008; Zimmerman, 2015):

- (1) To build the equipment for third parties that do not own the proper tools or necessary skill for such. This strategy is divided into the following possibilities:
 - to build the equipment of many suppliers of OSH technology;
 - to vary the catalogue of products of the company according to the demand, i.e. if a determined product is less interesting or becomes outdated and obsolete, it is possible to start manufacturing a more modern product quickly; and
 - to manufacture the components of open-source technology separately, such as mechanical parts made by 3D printers, electronic components or parts of printed circuit boards.
- (2) To explore commercially – through sales or negotiation of intellectual property – the extensions of OSHs that can be proprietary even if based on an open hardware.
- (3) Commercialization of technologies to develop OSH products (for instance, 3D printers, software for printed circuit boards, computational tools to promote the project, among others).

Other business possibilities for an OSH enterprise are related to the provision of high value-added services and of high technical specialization, as occurs in the software world (Watson, Boudreau, York, Greiner, & Wynn, 2008). In this case, the company that generates the project presents usually greater potential (Ferreira, 2008). Some of these possibilities are:

- (1) Adapting open-source technologies to the specific needs of customers;
- (2) Courses and trainings in several subject areas, such as:
 - operating OSH technologies;

- manufacturing/assembling a determined product;
 - manufacturing/assembling any OSH product; and
 - developing technologies based on the OSH paradigm.
- (3) Consulting on the best technical solutions, including proprietary items or open-source technologies:
- Renting spaces and infrastructure for companies and “maker” initiatives, i.e. the ones that manufacture OSH equipment[9].

Throughout the developed world (and a little in Brazil), it is possible to notice some companies that start to notice these possibilities and start to exploit them. Certainly, the most iconic company of this segment is the Italian Arduino, founded in the beginning of 2000s, whose products and services are related to its physical computer platform – a microcontroller based on the ATmega chip. Among the pioneers, one can also find Adafruit Industries, which explores businesses with diverse printed circuit boards, including microcontroller platforms known as feather boards, similar to the Arduino system. In 2013, Adafruit’s revenue was US\$23mn and its millionth order was made in 2016 (Adafruit, 2016). There are other companies that explore the open source in a profitable way, like Evil Mad Scientist Laboratories, Parallax, Lasersaur, Aleph Objects, 3D Robotics and SparkFun Electronics (Zimmerman, 2015), among others. The individual analysis of these companies, however, is beyond the scope of our study.

In Brazil, the exploration of the OSH market occurs usually in an indirect way. There are companies that provide products and services, such as printed circuit boards and 3D printing, who have certainly benefited from the emergence of OSH in the country, but they do not depend on OSH to succeed because there is still a high demand for proprietary technology in the country. For instance, Metamaquina, Cliever and Imprima 3D are companies operating in the field of 3D printing, which either commercialize the printers (resale or in-house production) or provide the service. On the other hand, there are probably dozens (or hundreds) of companies that manufacture printed circuit boards in the country for decades already.

Open Science Brasil[10] is an initiative more related to the OSH philosophy and is in the city of Ribeirão Preto, state of São Paulo, whose creation was accomplished by researchers from the University of São Paulo in Ribeirão Preto (USP-RP). The purpose of this initiative is to foster the democratization of the access to open-source tools for scientific research, including hardware tools. Despite being non-profitable, this initiative operates directly based on the OSH business model by bringing together all interested parties, such as the inventor of the technological solution, the customer (usually a scientist) and the producer (hardware hacker or maker) in mutual benefit transactions. Its main line of action is services related to a high value-added OSH product, known as Open Ephys. It is a system that records bioelectrical signals of the nervous system of laboratory animals. Such system is based on Intan® integrated circuits, which are considered revolutionary by the neuroscientific community because of its low cost and capacity to process, digitalize and transmit multiple channels of bioelectrical activity. Open Science Brasil enables (without exploring directly) the production and provides training and technical support of Open Ephys throughout the country.

Anyway, it is clear for anyone who performs research on the theme OSH or looks for specialized companies in Brazil that this is still a poorly explored subject in the country. When searching for the terms “open source hardware company,” using the language filter (Brazilian Portuguese), less than 30 results are found online (research carried out on December 4, 2017) – several results were in English despite the filter. When searching for the

terms “open source software company,” the results are around ten times greater. If this is a good or a bad sign for the business depends on the entrepreneur and his/her disposition to overcome the obstacles that the market imposes on novelties.

5.4 Open-source hardware: legal aspects

The application of laws and regulation in the open-model system may seem complex and delicate at a first glance, but this is not the real case. In fact, hardware is “born open” (Weinberg, 2015), which enables *a priori* the free reproduction and commercialization of technology in the OSH model.

To understand this aspect of OSH, it is necessary to differentiate the three main modalities of law on intellectual property: patent, copyright and trademark. The patent is the right to intellectual property over things that have a function, which is only accomplished when actively sought (through a patent deposit, for example) in a process that can be both long and costly. Still, this is not an assured right, because the patent is only granted when there is an effective innovation and novelty. The free reproduction and commercialization of a hardware becomes possible with the systemized publication of all pertinent information.

Copyright is the intellectual property on the result of creativity and encompasses artistic creations, such as movies, books, photography and music, as well as software source codes, usually understood as literature piece. This right, unlike patent, is acquired automatically when creating it and it hinders immediately the reproduction, adaptation or commercial exploitation by third parties. Keeping in mind that most part of the current hardware innovation is in conjunction with an embedded or even conventional software (in an interface with the computer, for example), the emission and the concession of a specific license is necessary to enable the free use of the code in the OSH model. Luckily, there are licenses such as Creative Commons or general public license that are widely disseminated and adopted by FOSS initiatives, and that can be immediately applied to the OSH case.

Finally, trademark is the exploration right of the commercial use over brands, whose major purpose is to ensure the reputation of companies by certifying the origin of a product or service. The obtention of trademark by an OSH company does not hinder its effective performance and the development of technology in the open model, once the mark is linked only to the use of the brand. One example is Arduino itself, a registered trademark that cannot be commercially explored by third parties, which is not a reason to impede the legal reproduction of its hardware in clones.

It is worth emphasizing that these observations were inspired by the American legislation, considering that the USA is the origin of most of the pertinent bibliography on the theme, and where one can find most efforts toward the OSH movement. It is possible, and even likely, that there may be different laws in different countries. That said, it is not the purpose of this paper to provide legal orientation on the matter; it is necessary to consult with a specialized lawyer to ensure the legal security of OSH enterprises.

5.5 Sustainability according to the open-source hardware paradigm

In the book “Open Source Lab” (2014), Joshua Pearce claims that:

In the work that my group focuses on – encouraging sustainability via technology development – ethical considerations also play a role. Is it ethical not to provide sustainability-related research information for free to others if so doing would be more likely to create a sustainable society? (Pearce, 2014, p. 42).

There are at least three obvious sectors in Brazil that present a high demand for sustainable development: health, education and science. They would all benefit from a synergy between the federal government and the private sector to foster technological innovation, particularly, open source like OSH and FOSS, given the scarcity of public resources in times of crisis.

In the area of education, there are obvious benefits that encourage the adoption of the OSH paradigm. The brutal reduction of costs inherent to open hardware could enable the entry of didactic technology, such as OSH microcomputers equipped with FOSS didactic software, microscopes and didactic sets for chemistry and physics, among others (Rossi, Benaglia, Brenna, Porta, & Orlandi, 2015) – especially in distant and poor regions in the country. Still, there is a high learning potential when students (from elementary school to engineering and technology undergraduate courses) are challenged to replicate or to develop new education-oriented OSH products, such as shown by a series of similar initiatives occurring around the world[11].

It is not hard to imagine the benefits of this strategy for health-related issues, because it is also directly related to costs. The Brazilian public health is a complex issue and its limited efficiency is determined by several factors. Yet, the cost of medical equipment for treatment, diagnosis, orthoses and prostheses, and also of devices to support medical procedures in intensive care units, is certainly one such factor that must be taken into account. It is possible, thus, to provide good medical care at a much lower cost when the open hardware approach is adopted, which indicates a broader access to medical technology. One extreme example is the ultra-low-cost centrifuge, which is provided as an open project, capable of reaching 125,000 rpm and a centrifugal force of 30,000 *g*; it can, therefore, separate plasma from blood in 1.5 min, isolating the malaria parasite in about 15 min (Bhamla *et al.*, 2017). Despite having a simple concept based on an ancient toy, the centrifuge was studied with scientific precision and excellency, which enabled its publication and open diffusion in a specialized journal (*Nature Biomedical Engineering*) of one of the most renowned editorial groups on the planet (Nature Publishing Group).

Finally, the benefits of the adoption of the OSH philosophy in the development of technology for science are also evident and have already been explored herein previously. It starts with the direct relationship of OSH philosophy with the mechanism of auto-correction that is indispensable to the functioning of science. It goes through the peer review, which tends to bring excellence to the solution, especially because of the possibility to adapt it to particular needs. Finally, the use of OSH is justifiable by the probable strong cost reduction, which minimizes the impact of funding inherent to research, bringing closer small and the large laboratories; or, according to the neuroscientist Dr Eve Marder, the “haves” and the “have nots” (Marder, 2013).

6. Academic perspectives and final considerations

The natural and intense evolution in understanding the mission of university, the impetus and the nature of entrepreneurs as well as the brutal technological transformation over the past decades, puts in discussion the models of entrepreneurship and technological innovation as a central discussion not only in the corporate environment, but especially in the academic sphere. The purpose of this paper is in line with such statements, because when presenting the several aspects of the open model – properly based on theoretical frameworks of academic entrepreneurship – we contribute to this discussion bringing about the little explored OSH concept. However, this subject is far from being concluded and there are several other scientific investigations to be developed.

One of the main investigation paths is certainly the individualized observation of OSH companies operating in Brazil or elsewhere in the world, or even the panoramic and qualitative registration of a regional ecosystem of open sources. Certainly, it is also important to study OSH initiatives within universities through, for instance, objective measures in empirical studies that approach entrepreneurship based on this model, especially in comparison to the conventional traditional model. It seems plausible, but only an effective investigation will establish the hypothesis that the adoption of the open-source model in the entrepreneur university is more natural than the closed one, considering that its nature and characteristics favor the development of knowledge. Such as that happens with academic entrepreneurship, it is important to map risk and success factors within the OSH model by establishing correlations with performance variables, such as academic productivity; creation and survival of startups and spinoffs; and regional social and economic development. Finally, it is important to perform extensive studies, perhaps as systematic reviews, capable of making a qualitative or quantitative comparison between conventional technological innovation models and OSH.

This set of studies will enable the definition of new theoretical frameworks capable of better incorporating the disruptive potential of non-conventional models (such as OSH), which, after transmitted through the several initiatives of entrepreneurial education, will cooperate to understand the phenomena of entrepreneurship and innovation in a broader way, enabling the elaboration and adoption of policies to support them.

It is also necessary to recognize that in turbulent social and economic moments Brazil usually goes through, the future is, at least, obscure. To pursue an entrepreneurial adventure, especially a non-conventional one, may seem a bit too risky. On the other hand, complex situations sometimes demand uncommon and different solutions. The definition of entrepreneur given by Joseph Alois Schumpeter is in line with such observations; according to the author, the entrepreneur is someone who creates new combinations of elements; introducing new products and/or processes; and identifying new consumption markets or sources of supply, therefore creating new types of organization (Schumpeter, 1943).

Furthermore, there are several factors in the Brazilian and in the world context, such as the arguments mentioned herein, that can boost and encourage alternative models of sustainable development, as it seems to be the case of OSH. In this sense, the opportunity entrepreneurship is a viable (and with great potential) tool to seek for technological innovation through open hardware in the areas of health, education, science and others.

Notes

1. Brazilian Society for the Progress of Science, in English.
2. State Department for Science, Technology and Higher Education, in English.
3. Brazilian Micro and Small Enterprises' Support Service, in English.
4. Innovation Incentive Program, in English.
5. São Paulo Research Foundation, in English.
6. Retrieved from <https://www.oshwa.org/definition/>
7. Retrieved from <https://www.oshwa.org/about/>
8. Retrieved from <http://retrap.org/>

9. For further information, check the concept of Makerversity available at <http://makerversity.org>.
10. For further information, check <http://opensciencebr.com/>
11. Check Trend in Africa: <http://trendinafrica.org/>

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